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Using a hierarchical model framework to assess climate change and hydropower operation impacts on the habitat of an imperiled fish in the Jinsha River, China

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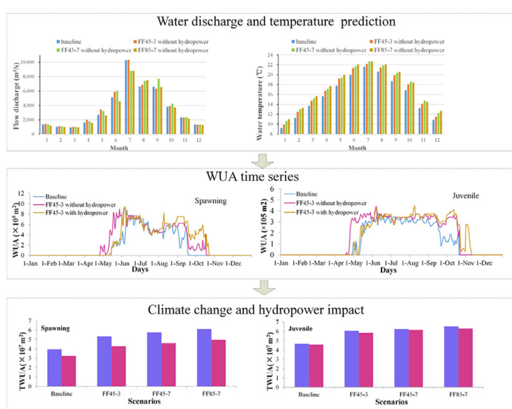
HIGHLIGHTS

- Impacts of climate change and hydropower on fish habitat were predicted and evaluated.
- Habitat suitability increased caused by climate change but decreased by hydropower.
- The habitat area would still increase under their combined impacts.
- Water temperature regime change is the main factor of their opposite impacts.
- Habitat change will lead to shift of spawning activity of fish species.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change and hydropower operations affect hydrological regimes at regional basin scales and impact hydrodynamics and habitat conditions for biota at the river reach scale. The present study proposes a hierarchical modeling framework for predicting and analyzing the impacts of climate change and hydropower on fish habitats. The approach couples multi-scale climate, hydrological, water temperature, hydrodynamic and habitat suitability models and was applied to a reach of the Jinsha River. Flow discharge and water temperature were predicted in the study area for a baseline scenario and three climate change scenarios, and each considered the presence and absence of impacts caused by hydropower operation. The impacts of flow discharge and water temperature variations on spawning and juvenile *Coreius guichenoti*, an imperiled warm-water fish in the Jinsha River Basin (JRB), were evaluated using a fuzzy logic-based habitat model. The results showed that habitat suitability and available usable area for the fish increased due to climate change, and water temperature rising was the main influencing factor. Water temperature decrease induced by hydropower operation in the spawning

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Scenario prediction
Warm-water fish
Fish spawning

periods resulted in the reduction of available habitat area. However, climate change reduced the negative effects generated by hydropower operation, and the available habitat area for the fish would still be expected to increase under the combined impacts of climate change and hydropower operation in the future. It is predicted that water warming, as a result of climate change, is likely to eliminate the spawning postponement effect generated by hydropower operation on *Coreius guichenoti* as well as other warm-water fish species in the JRB. In contrast, water warming induced by climate change is likely to exacerbate the negative effects of hydropower operation on the spawning activity of cold-water fish species in the JRB. The present study provides a scheme to predict the impacts of climate change and hydropower on other organisms in river ecosystems. The results are beneficial for the development of long-term and adaptive conservation and restoration measures for aquatic ecosystems.

1. Introduction

Freshwater ecosystems provide services for human life and terrestrial productivity and contain some of the most imperiled communities on Earth (Abell, 2002; Heino et al., 2009). Several studies and observatory campaigns have revealed that these ecosystems are threatened by climate change and anthropogenic activities (Comte et al., 2013; Hauer et al., 2013; Junker et al., 2015; Brown et al., 2016). These threats have led to freshwater biodiversity declining at a faster rate than that of terrestrial or marine biodiversity (Jenkins, 2003; Dudgeon et al., 2006).

Climate change is expected to increase stream temperatures and alter flow regimes, and it represents one of the most significant threats to stream fishes (Ficke et al., 2007; Palmer et al., 2009; Woodward et al., 2010). Fish species have specific temperature thresholds and precipitation tolerances from which species distributions are shaped. The shifts on temperature and hydrological regimes will ultimately alter the habitat conditions of freshwater species (Schindler, 2001). Several studies have predicted substantial habitat losses for cold-water stream fishes that will be impacted by increases in stream temperature (Mohseni et al., 2003; Preston, 2006; Null et al., 2012). For instance, an analysis of the climate change impacts on four trout species across the interior western United States indicated an expected reduction in total suitable habitat of 47%; this reduction was driven by increases in temperature and winter flood frequency as well as flow regime shifts (Wenger et al., 2011b).

Moreover, habitat alterations are also increasingly caused by human activities (e.g., channelization, dredging, damming, and land-use change) (Allan, 2004; Bobbi et al., 2014). Habitat modifications often result in altered and degraded stream conditions, fragmented habitat conditions and degraded aquatic biodiversity (Wu et al., 2003). Anthropogenic habitat alterations, combined with changes in stream temperatures and flow regimes, will likely cause persistent declines in aquatic biota (Dudgeon et al., 2006; Sievert et al., 2016). There have been many studies that have assessed water temperature and hydraulic changes caused by human activities, and physical habitat models have been used to evaluate the effects of these changes on fish habitat (Im et al., 2011; Yi et al., 2014; Pragana et al., 2017). However, in order to plan for long-term biodiversity conservation, a better understanding of how anthropogenic impacts and threats affect aquatic species is needed (Turner et al., 2003; Poff et al., 2012).

Most of the studies aimed at determining climate change impacts on freshwater fish habitat have focused on cold-water fish species (Rahel et al., 1996; Null et al., 2012), on thermal suitability under climate change (Mohseni et al., 2003; Sharma et al., 2007; Ficklin et al., 2013; Brown et al., 2016), or on flow discharge suitability (Hauer et al., 2013; Papadaki et al., 2016; Segurado et al., 2016). Few studies have considered the combined influences of the two factors on habitat of warm-water fish species (Mantua et al., 2010; Wenger et al., 2011a). Moreover, studies of combined future climate change and human activity impacts on fish habitat are scarce (Guse et al., 2015).

Among the different available approaches, physical habitat simulation has emerged as a powerful tool to quantify variations in suitable habitat for different river biota (Bovee, 1998). To assess the impacts of climate change on stream fish habitat, it is necessary to identify the changes in stream temperatures and flow regimes (Malmqvist and Rundle, 2002). Moreover, this type of approach typically relies on several coupled models, such as a climate model that has been downscaled to a regional area, a watershed hydrological model, a water temperature model, a hydraulic model and a habitat suitability model (Munoz-Mas et al., 2016). In fact, such a hierarchical model framework has been tested to assess the effects of different pressures on abiotic habitat conditions and river biota (Guse et al., 2015; Jochem Kail et al., 2015).

The main aim of this study is to develop a multi-scale coupled hierarchical model framework to assess the impacts of climate change and hydropower operation on the habitat conditions of spawning and juvenile *Coreius guichenoti* (*C. guichenoti*), a warm-water fish in the Jinsha River Basin (JRB), which is an area that is highly sensitive to climate change and is largely altered by hydropower development. First, the hydrology, hydrodynamics, water temperature and fish habitat suitability were consecutively simulated along the model cascade under climate change with and without hydropower operation scenarios. Second, the impacts of climate change and hydropower operation on flow discharge and water temperature were evaluated in the study area. Finally, the relevance of changes between habitat factors (i.e., flow discharge and water temperature) and habitat quality and the potential impacts on spawning activities of fish species were analyzed in the JRB.

2. Study area

The JRB (90° 23′E–104° 37′E, 24° 28′N–35° 46′N) is located at the western margin of the Tibetan Plateau, the Yunnan-Guizhou Plateau and the Sichuan basin in China. Originating from the southern glacier at the Jianggendiru peak of the Geladaindong Snowy Mountain in the middle of the Tanggula Mountains, the Jinsha River is an upstream portion of the Yangtze River. The JRB covers an area of approximately 540,000 km^2. The total length of the mainstream Jinsha River is 3500 km, with a total fall of 5100 m; this accounts for 55.5% of the length and 95% of the total fall of the Yangtze River. The JRB belongs to the plateau climate zone, and the air temperature progressively increases from upstream to downstream. The general distribution of precipitation in the JRB gradually increases from the northwest to the southeast. The flooding season in the JRB lasts from June to October, which is when 75%–85% of the rainfall occurs.

The JRB is the most biodiverse region of China and has a rich variety of freshwater fishes. There are as many as 177 fish species endemic to the JRB for its unique environmental characteristics. The basin also has great potential as a source of hydropower. The development of cascaded hydropower dams on the Jinsha River was proposed in 2005, and thereafter, several large dams were constructed. The built and under-construction large dams on the JRB are presented in Fig. 1. The construction and operation of such dams and reservoirs has already negatively influenced the habitat quality of *C. guichenoti*, an important endemic, economically valuable and anadromous migratory fish species in the JRB. It is a eurythermal fish with a preference for warm waters; furthermore, the water temperature must be above 18 °C to initiate spawning (Liu et al., 1990; Cheng et al., 2015). The spawning period of the fish is

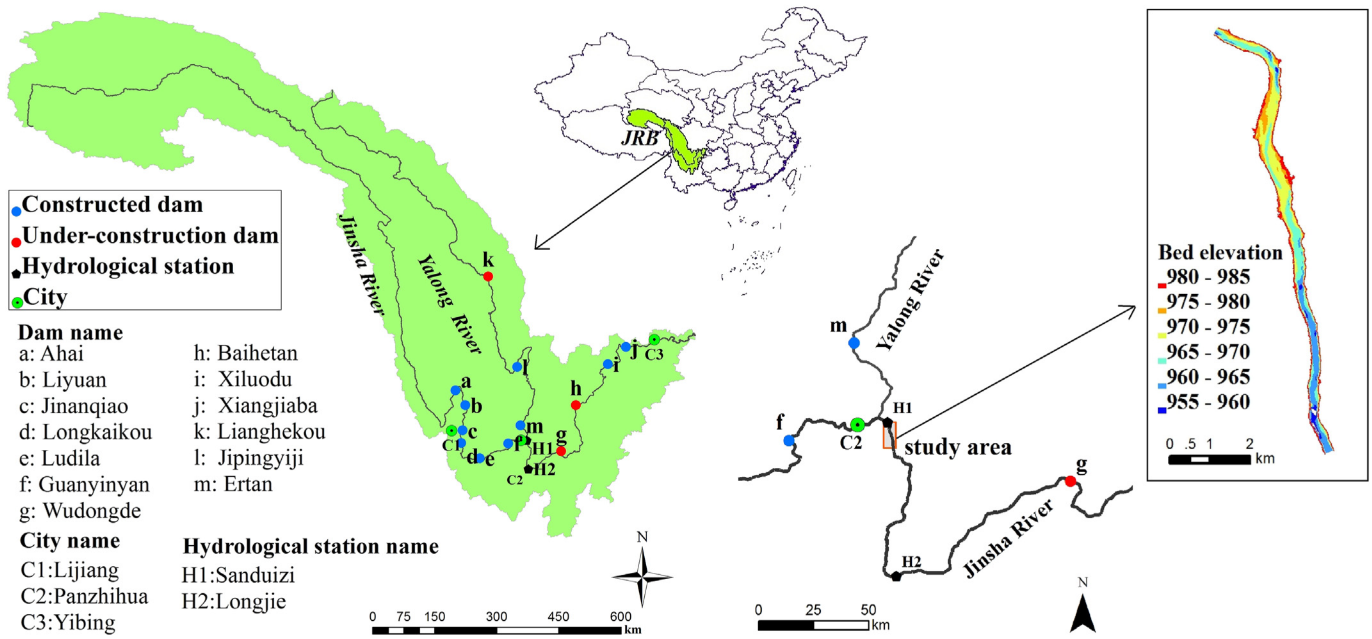

Fig. 1. The Jinsha River Basin and the studied river reach.

from May to July, and it travels from the lower to the upper reaches of the Jinsha River. Therefore, the presence of cascade dams has decreased the river connectivity, blocked the migration passage, and fragmented the habitat of *C. guichenoti* (Tang et al., 2012). The protection priorities for the 16 endemic fish in the upper Yangtze River were analyzed, and the results showed that *C. guichenoti* was seriously affected by environmental changes; thus, the species is in urgent need of protection (Liu, 2004).

Many field sampling campaigns have been conducted on the main stream of the Jinsha River, and the river reaches near the Panzhihua City in the middle Jinsha River were identified as important spawning grounds for *C. guichenoti* (Tang et al., 2012; Yang et al., 2017). In this study, a river reach located downstream from the Yalong River mouth was selected as a representative study area of the JRB (Fig. 1). The Yalong River is the largest tributary of the Jinsha River and flows into the Jinsha River near the Panzhihua City. The studied river reach is approximately 10 km long and is located downstream of a hydrological station named Sanduizi. Spawning and juvenile *C. guichenoti* were selected as the target groups for this study. A multi-scale coupled eco-hydrological hierarchical model framework was developed to analyze the impacts of climate change and hydropower operation on fish habitat conditions.

3. Methodology

3.1. Hierarchical model framework

The modeling and analysis of aquatic ecosystems is often a complex task. A combination of separate models must be used to capture the different relationships in a river ecosystem, and each describes a specific aspect of the problem. To simulate habitat suitability in the studied river reach, a hierarchical model framework was developed to incorporate a climate model, hydrological model, water temperature model, hydraulic model and habitat evaluation model at different scales, and their impacts on fish habitat suitability were assessed. The hierarchical model framework is shown in Fig. 2.

First, global climate models were used and downscaled to the JRB to provide meteorological data for the basin. The meteorological data and the data of the hydropower operation scheme were used as input data for the hydrological model at the scale of the JRB. Then, the river flow discharge data calculated by the hydrological model and the meteorological data from the previous climate models were used as input for a water temperature model at a river segment scale. The river flow discharge data were also used as input for a one-dimensional (1D) hydraulic model used to predict water levels in river segments. Finally, a two-dimensional (2D) hydraulic model and a habitat evaluation model were established for the studied river reach. The flow discharge data predicted from the previous hydrological model and the water level data predicted from the 1D hydraulic model were used as inputs into the 2D hydraulic model. Hydrodynamic data (i.e., water depth and velocity) from the 2D hydraulic model and water temperature data from the previous water temperature model were used in the habitat model to calculate and evaluate habitat suitability for spawning and juvenile *C. guichenoti*. The models mentioned above are described in detail in the following sections.

3.2. Climate models

In the context of the Sino-Swiss project entitled “Jinsha River Basin (JRB): Integrated Water Resources and Risk Management under a Changing Climate” (i.e., the JRB project) (Swiss Agency for Development and Cooperation, 2016), a set of 24 climate change scenarios were developed. These scenarios resulted from a combination of 11 General Circulation Models (GCMs) and two Representative Concentration Pathways (RCPs, RCP 4.5 and RCP 8.5) calculated for the near future (NF, 2021–2050) and far future (FF, 2070–2099) periods. The period from 1981 to 2010 was used as the baseline period. A total of 18 GCMs were available along with the 2 RCPs. The scenarios were selected based on the following three criteria. First, the past performance of the 18 GCMs at annual and seasonal temperature and precipitation scales were studied in terms of the Mann-Kendall coefficient and linear trend rate. Second, the absolute change in temperature and the relative change in precipitation with respect to the baseline period should represent a broad response and not average climate change, i.e., the selected GCMs must include the 10% and 90% quantiles. Third, the selected GCMs must stem from independent climate modeling centers to avoid systematic bias. The final selection of the 11 GCMs was based on expert judgment and was based mainly on criterion 1. The final selection of the GCMs is shown in Table 1. The selected GCMs were then downscaled to the JRB region using the delta change method, and

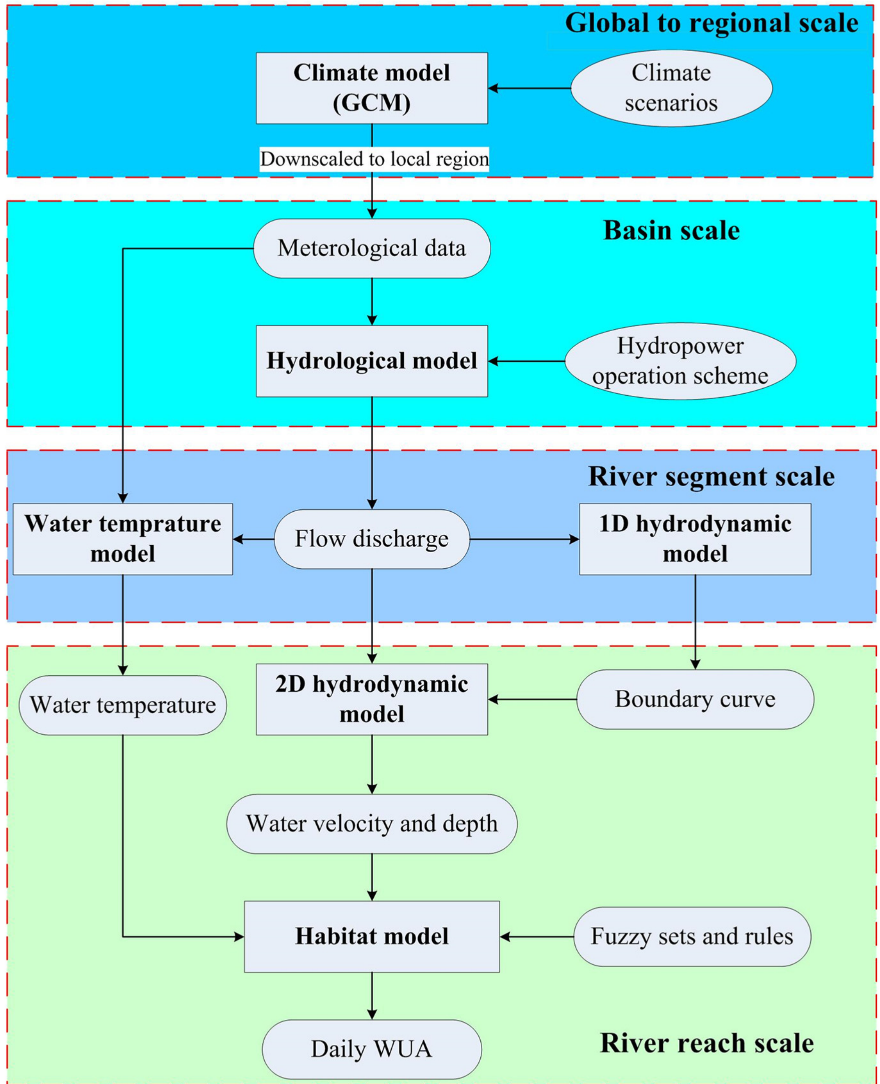

Fig. 2. The hierarchical model framework.

meteorological data (i.e., daily air temperature and precipitation) were produced for the JRB. Only three climate scenarios (i.e., FF45-7, FF45-3 and FF85-7) were retained for this study. The selection criteria are detailed in Section 3.7.

Table 1
Abbreviations of the different climate change scenarios used in this study. NF and FF denote the near future and far future periods, respectively. The selected climate change scenarios were in bold (e.g., FF45-7 represents scenario ACCESS1-3 with RCP 4.5 for far future periods).

GCM	Near future (2021–2050)		Far future (2070–2099)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
ACCESS1-3			**FF45-7**	
BNU-ESM			FF45-5	FF85-5
CCSM4		NF-6		FF85-6
FGOALS-g2		NF-1	FF45-1	FF85-1
FIO-ESM	NF-7			**FF85-7**
GFDL-ESM2G	NF-8		FF45-8	
GISS-E2-H				FF85-8
HadGEM2-ES		NF-2	FF45-2	FF85-2
IPSL-CM5A-LR		NF-5	FF45-6	
IPSL-CM5B-LR		NF-3	**FF45-3**	FF85-3
MIROC5		NF-4	FF45-4	FF85-4

3.3. Hydrological model

The hydrological conditions in the JRB were modeled using the Routing System (RS) model (Hernandez et al., 2007). The RS model simulates rainfall-runoff processes as well as flow routing based on a semi-distributed conceptual scheme. The rainfall-runoff modeling is based on the GSM-SOCONT (Glacier-Snow Melt Soil CONTribution) model, which considers numerous hydrological processes, such as snowmelt, glacier melt, surface and underground flow due to infiltration and simple karstic behavior (Schaefli et al., 2005). The discretization of the basins into elevation bands meets the need of including temperature variation with altitude. When necessary, the elevation bands include a glacier melt model that replaces the soil infiltration model. Hydraulic structures, such as water diversion, reservoir storage and reservoir routing, as well as water allocations, can also be integrated into the model.

A specific model has been developed for the JRB. Based on the river network and the location of the discharge gauging stations that provide historical and real-time data, the JRB basin was divided into 53 subcatchments, which were further divided into 1146 runoff generation units or altitude bands. A total of 13 large dams and reservoirs were included in the model (Fig. 1); of these, 9 have a dam height > 100 m, and 12 have a production capacity > 2000 WM. The reservoirs are characterized by a relationship between water level and reservoir volume. At

each time step, this relation is used to define a mass balance between the inflows, the outflows (i.e., hydropower production, spillway releases, or evapotranspiration) and the variation in water storage. The exploitation criteria considered aim to maximize hydropower production while maintaining safety. Thus, whenever the inflow is expected to raise the water level beyond a certain threshold, the spillways will release water from the reservoir. The model was calibrated for recent periods and used to predict the flow discharge in several climate change scenarios. The flow discharge data from Sanduizi (H1 in Fig. 1) were selected and used for the studied river reach.

3.4. Water temperature model

A water temperature model was established to simulate the water temperature in the studied river reaches based on the results from the RS model. The model was coupled with the hydrological model. The water temperature model was composed of groundwater, seasonal and daily signals. The groundwater temperature is supposed to be constant and depends mainly on the groundwater temperature and the soil temperature; in contrast, the seasonal and daily signals depend on the air temperature. The parameters included in the model consider the shading effects caused by the vegetation and topography. Heat exchanges are also considered at the river reach scale. The input data for the water temperature model include the incoming shortwave radiation, mean wind speed, air pressure, air temperature and humidity. The daily water temperature data measured at the river reaches were used to calibrate the model.

However, heat exchanges in large reservoirs were not computed due to the lack of bathymetric information needed to characterize such a complex hydrodynamic system. Therefore, the hydropower operation effect was not considered in the water temperature model. A correction factor was applied to the results of the scenarios without hydropower operation to contextualize the scenarios affected by hydropower operation. This correction factor was defined as the difference between the observed monthly averaged water temperature with and without the influence of hydropower. For this, the considered representative periods were 2001–2003 for the assumption of no hydropower influence (i.e., the period before dam construction) and 2012–2014 for the case with hydropower influence (i.e., the period after dam operation). This correction factor indicates an increase in water temperature from 0.2 to 2.8 °C from July to January and a decrease in water temperature from −0.9 to −2.5 °C from February to June due to the impacts of hydropower operation (Fig. 3). Therefore, the daily water temperatures for the scenarios influenced by hydropower operation were estimated by adding the correction factor to the predicted water temperature for the scenarios

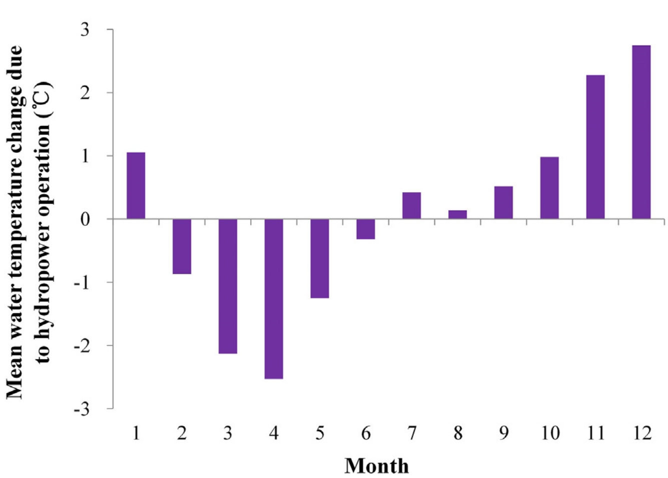

Fig. 3. Correction factor calculated as the monthly mean water temperature difference between the period before dam construction (2001−2003) and the period after dam operation (2012–2014).

without hydropower. Using this model, the daily water temperatures for the studied river reaches were predicted for all scenarios.

3.5. 1D and 2D hydrodynamic models

The two-dimensional hydrodynamic model River2D (Steffler and Blackburn, 2002) was used to evaluate the hydraulic habitat conditions (e.g., flow velocity and water depth) of the studied river reach. River2D numerically solves the basic mass conservation equation and the two horizontal components of momentum conservation to calculate the two horizontal flow velocity vectors and the water depth.

Since the water level data at the outlet of the study river reach were unavailable, a 1D hydrodynamic model based on Mike11 was elaborated. This model works in a quasi-steady mode and is used to predict water levels for the 2D model. In this study, the 1D hydrodynamic model was set up for a river reach from Sanduizi (H1) to Longjie (H2) (Fig. 1, right). The river reach was divided into 125 cross sections, with a distance of ~800 m between sections. The 11th cross section of this 1D model corresponds to the lower boundary of the studied river reach. A water level-discharge curve was characterized from this model as the lower boundary condition for the 2D hydrodynamic model. The 2D model was established with a grid resolution of 30 m. The water velocity and depth were predicted by the 2D model for the different inflows in all baseline and future scenarios.

3.6. Habitat suitability model

The habitat model CASiMiR-GIS (Schneider et al., 2012) was applied to assess and quantify the habitat suitability for the spawning and juvenile *C. guichenoti* in the studied river reach. This model is a fuzzy logic-based habitat evaluation model that can be applied to rivers that differ in size, flow regime, and riverbed structure (Noack et al., 2013). In a GIS environment, the model can define any parameter using GIS functionalities and can apply all GIS features to visualize habitat suitability maps and further analyze the simulation results. The fuzzy logic concept is used in the model by constructing the fuzzy sets of habitat factors and fuzzy rules based on available habitat data and knowledge from ecological experts (Mocq et al., 2013).

In this study, three key habitat factors, i.e., water temperature, velocity and depth, were considered for spawning and juvenile *C. guichenoti* in the fuzzy-logic based habitat model. The resulting fuzzy sets of habitat factors for spawning and juvenile fish are displayed in Fig. 4. Each input habitat factor and output habitat suitability index (HSI) were expressed with linguistic categories: 'very low (VL)', 'low (L)', 'medium (M)', 'high (H)' and 'very high (VH)'. The fuzzy rules for spawning and juvenile *C. guichenoti* are presented in the Appendix, in Table A-1 and Table A-2. After the fuzzy sets of input variables and fuzzy rules were established, a habitat evaluation was conducted for the different scenarios.

Outputs from the habitat suitability models are expressed as the Weighted Usable Area (WUA) (Eq. (1)), which is calculated to quantitatively assess the habitat condition or availability of the entire river reach. Because water temperature, velocity and depth were considered in the habitat model of this study, the WUA was calculated for any given water temperature and flow discharge.

$$\mathrm{WUA} = \sum_{i=1}^{n} A_i HSI_i = f(Q, T) \tag{1}$$

where A_i is the area of the ith cell of the 2D hydrodynamic model grid, HSI_i is the suitability index in the ith cell, n is the number of model cells, and Q and T are the given flow discharges and water temperatures, respectively, in the studied river reach.

Because *C. guichenoti* produce pelagic eggs, the fish eggs are transported to the downstream reach of the of the study area. The egg collection campaigns were conducted in Jiaopingdu sampling section downstream of the study area in the spawning months in 2013 and

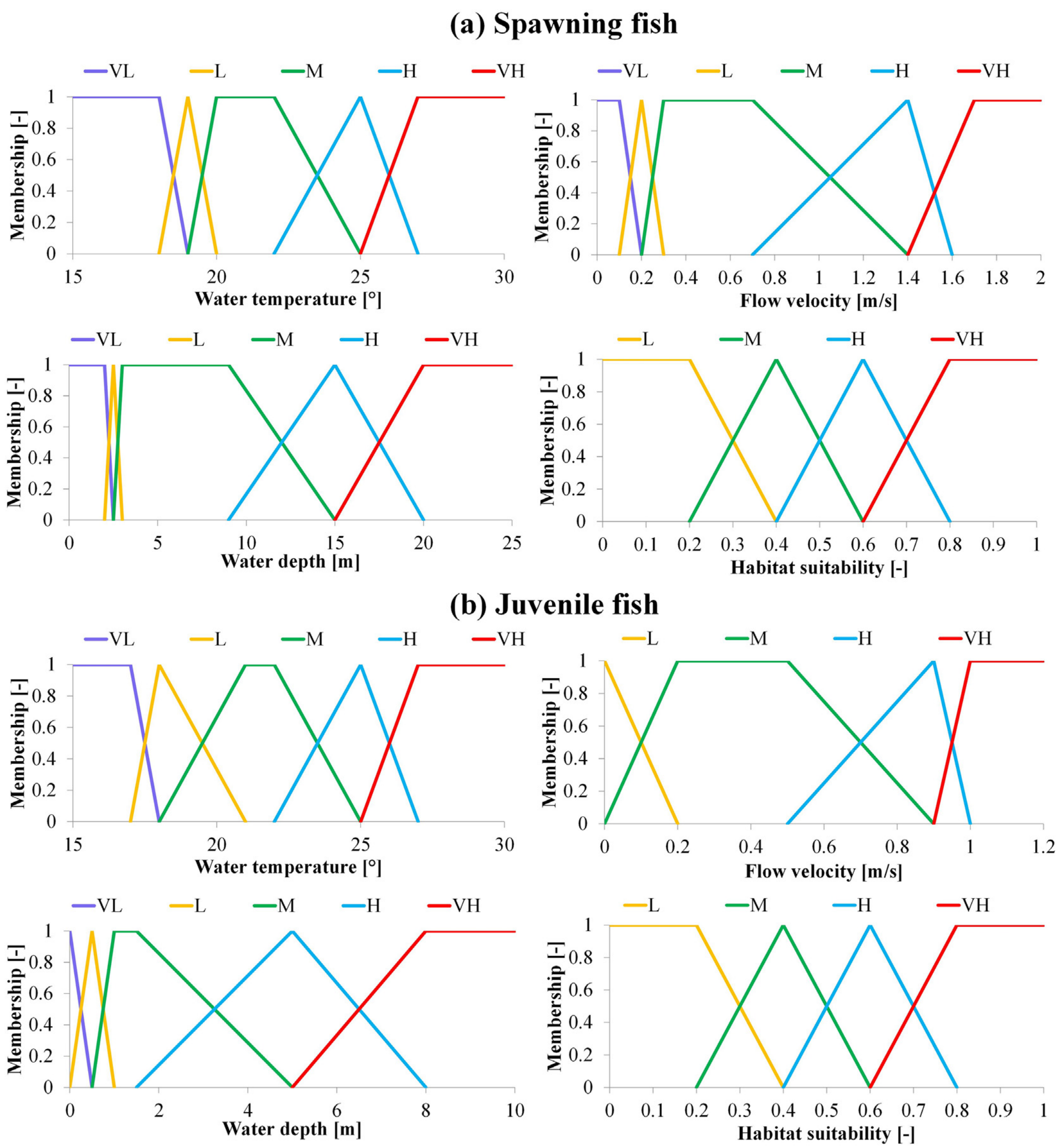

Fig. 4. Membership functions for the input variables of water temperature, velocity, and depth and for the output variable of habitat suitability for spawning and juvenile *C. guichenoti*.

2014 to collect eggs produced by the fish in the study area. The daily spawning eggs in the study area were estimated using the method described by Xu et al. (2015). By comparing the WUA and number of the spawning eggs, the habitat model was validated in this study.

3.7. Model scenarios

Water discharges for all climate change scenarios were predicted using the hydrological model. In this study, the water discharge ratios between the climate change scenarios and the baseline at Sanduizi Station during the wet season were calculated. Based on the discharge ratio values, the maximum, minimum and median scenarios, i.e., FF45-7, FF85-7 and FF45-3, respectively, were selected (Table 1). The water discharge ratio values for FF45-7, FF85-7 and FF45-3 were 1.12, 0.98 and 1.06, respectively. The scenario FF45-7 (ACCESS1-3 with RCP 4.5 from 2070 to 2099) represents the maximum increase in water discharge impacted by climate change; FF85-7 (FIO-ESM with RCP 8.5 from 2070 to 2099) represents the minimum decrease in water discharge impacted by climate change; and FF45-3 (IPSL-CM5B-LR RCP 4.5 from 2070 to 2099) represents the median observed increase in discharge.

For the baseline and each climate change scenario, two cases were investigated:

- Without the influence of hydropower operation to evaluate the independent effect of climate change. For this case, the hydropower elements were removed from the hydrological model.
- Including the influence of hydropower operation to evaluate the combined effects of climate change and hydropower. For this case, the complete hydrological model, including the hydropower elements, was used.

Table 2
Scenarios used in this study.

Description	Scenario name	Scenario used in this study
Baseline discharge scenario	Baseline	Baseline without hydropower Baseline with hydropower
Maximum discharge scenario	FF45-7	FF45-7 without hydropower FF45-7 with hydropower
Medium discharge scenario	FF45-3	FF45-3 without hydropower FF45-3 with hydropower
Minimum discharge scenario	FF85-7	FF85-7 without hydropower FF85-7 with hydropower

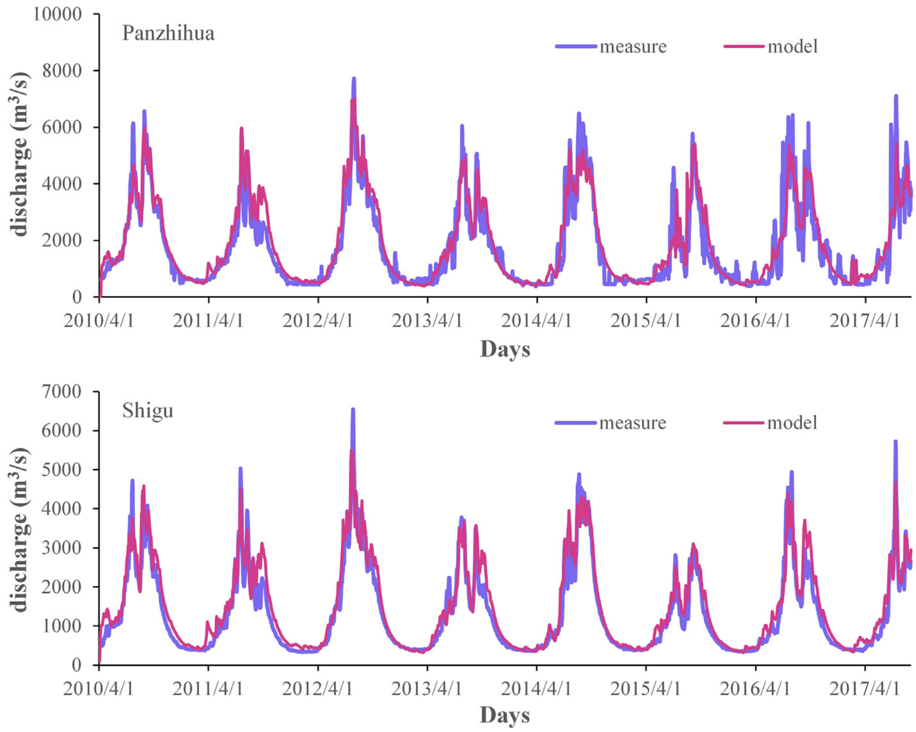

Fig. 5. Comparison of measured and simulated daily flow discharge at Panzhihua and Shigu stations.

Therefore, a total of eight scenarios were employed in this study (Table 2). Based on 30 years of water discharge data for each scenario, the normal discharge years were selected using hydrologic frequency analysis. Daily flow discharges and water temperatures in the study river reach for the normal year for each scenario were predicted to provide data for the hydraulic and habitat models. Daily habitat suitability and WUA were calculated for each scenario.

4. Results

4.1. Flow discharge and temperature

4.1.1. Model calibration and validation

The hydrological model of the JRB was calibrated using daily water discharge data from 52 hydrological stations for the period 2010–2015, and was validated for the period 2016–2017. The model was calibrated by maximizing the Nash and log-Nash values and minimizing the relative volume bias. A comparison between the simulated and measured flow discharges at the Panzhihua Station, which is located just upstream of the study area, and the Shigu Station, which is located in the upper reaches of the Jinsha River, are displayed in Fig. 5. The model adequately reproduced the flow with good performance indicators. For Panzhihua Station, the Nash and log-Nash values were 0.77 and 0.88, respectively, and the relative volume bias was −1%. For Shigu Station, the results were 0.78, 0.92 and +7%, respectively. The model was also verified for the baseline period of 1981–2010. However, for this period, only monthly data were available. For the verification at Panzhihua Station, the Nash and log-Nash values were 0.94 and 0.93, respectively, and the relative volume bias was +6%. For the verification at Shigu Station, the results were 0.92, 0.92 and +8%, respectively.

The water temperature model of the studied river reach was calibrated using the water temperature data registered at Sanduizi Station from 2012 to 2014. Fig. 6 shows the model results compared with the observations at a daily resolution for the studied period. The general performance of the model was good, and the seasonal variation in water temperature was well reproduced. The Nash and RMSE values

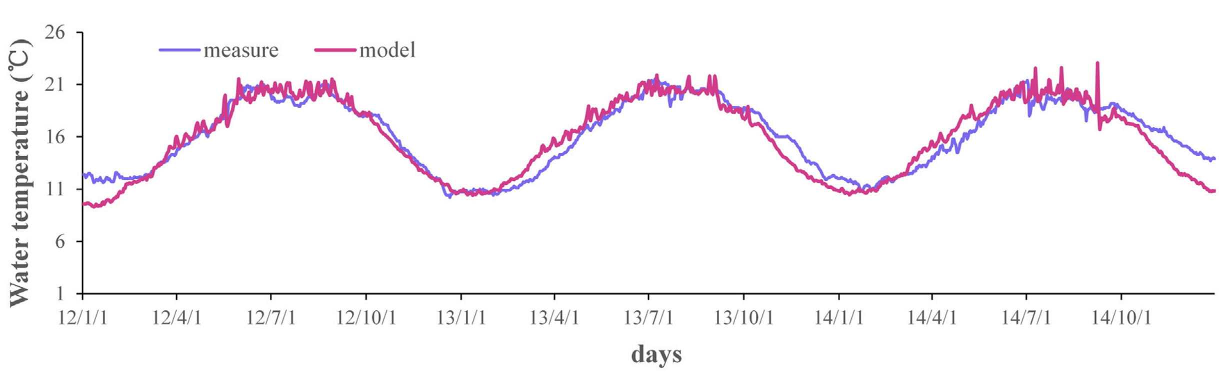

Fig. 6. Comparison between the measured and simulated water temperatures at Sanduizi from 2012 to 2014.

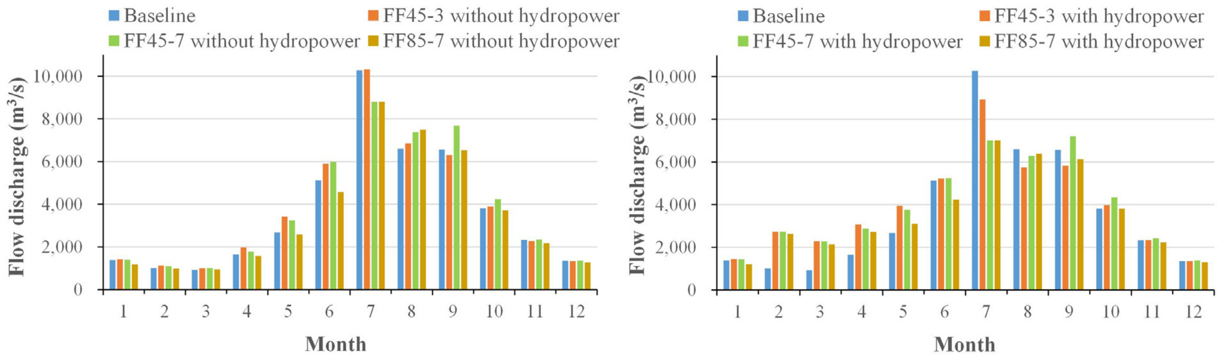

Fig. 7. Comparison of baseline and predicted monthly mean flow discharge at Sanduizi for different climate scenarios without considering (left) and with considering (right) hydropower operation.

were 0.87 and 1.12 °C, respectively. The results showed larger differences during the months from October to January, during which the modeled temperature tended to be lower than the measured temperature. It is worth mentioning that the temperature model was not able to simulate the temperature exchanges in large reservoirs. This difference was mainly due to the heat exchanges after the wet season when the reservoirs tended to be full. However, the general results were satisfactory, with a mean absolute difference between the modeled and measured water temperatures of 0.94 °C. The performance of the model increased during the wet season (i.e., June to September), with a mean absolute difference of 0.73 °C. The water temperature model was employed to predict the daily water temperature for the baseline and climate change scenarios without considering hydropower operation. For scenarios that considered the influence of hydropower, the water temperatures were obtained by adjusting the modeled results using the monthly mean temperature correction factor (Fig. 3) that described in Section 3.4.

4.1.2. Future scenario modeling

Using the calibrated hydrological model, the flow discharge and water temperature in the study area were predicted for the eight scenarios described in Section 3.1. Fig. 7 depicts the comparisons of the monthly mean flow discharges between the baseline and climate change scenarios. For the cases without hydropower (Fig. 7, left), the flow discharges were generally higher under the climate scenarios FF45-3 and FF45-7 (except for a distinct 14.2% decrease in July for FF45-7 and a slight decrease in September for FF45-3). This tendency changed under the FF85-7 scenario, where a general decrease can be detected (except for a 13.6% increase in August). For the cases with hydropower (Fig. 7, right), the flow discharges further increased from February to May (mostly >65%) under all climate scenarios; however, they declined slightly over the rest of the year (except for some increases >10% in September and October in FF45-7).

A comparison between the monthly mean water temperatures is shown in Fig. 8. In general, the mean water temperature is expected to increase in each month under the three climate scenarios without the consideration of hydropower operation (Fig. 8, left). For each month, the FF85-5 scenario increased water temperature the most, while the FF45-3 scenario increased water temperature the least. The mean temperature increases for FF45-3, FF45-7 and FF85-7 were 1.02 °C, 1.52 °C and 1.77 °C, respectively. For the climate change with hydropower scenarios (Fig. 8, right), water temperatures decreased from 0.2 to 1.4 °C in March and April and increased over the rest of the year. Comparing with the climate change scenarios without hydropower, the water temperatures further increased from August to January for the climate change scenarios with hydropower; the monthly mean increase in water temperatures in this period for FF45-3, FF45-7 and FF85-7 were 2.19 °C, 2.79 °C and 2.91 °C, respectively. Although the water temperature slightly decreased in February, May and June in the climate change scenarios with hydropower, they were still higher than the baseline.

4.2. Habitat suitability

4.2.1. Model verification

The habitat model for spawning fish was verified using 21 groups of daily egg numbers estimated from the monitoring data from Jiaopingdu. The model results showed that the daily number of eggs was well

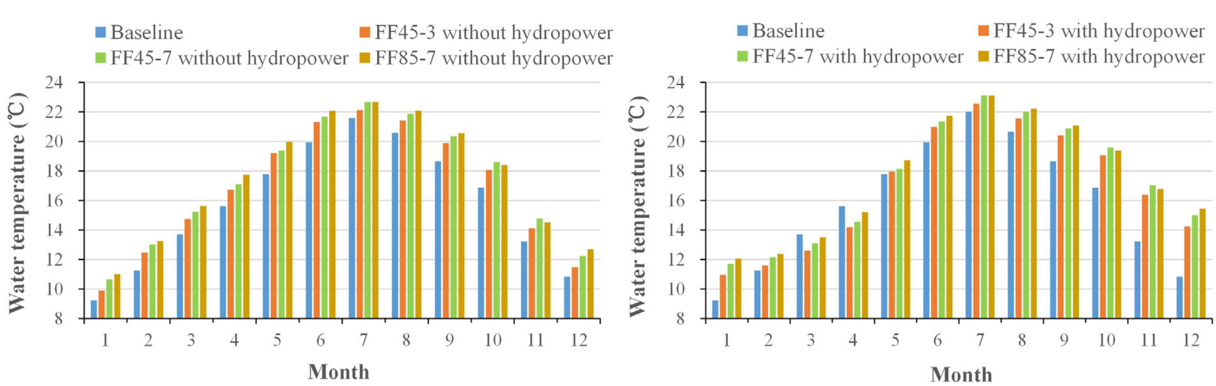

Fig. 8. Comparison of baseline and predicted monthly mean water temperatures at Sanduizi for different climate scenarios without considering (left) and with considering (right) hydropower operation.

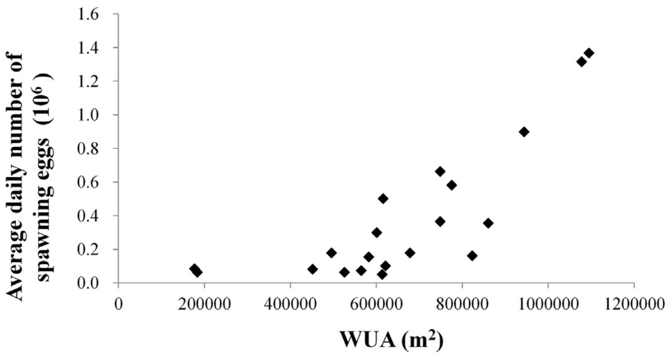

Fig. 9. Relationship between the daily spawning egg numbers and the simulated WUA in the studied river reach.

correlated with the WUAs (Fig. 9), with a Pearson correlation value of 0.79 ($p < 0.05$). This result indicated that the model was valid for the simulation of habitat suitability for spawning *C. guichenoti* in the study area. Because biomass data for juvenile *C. guichenoti* are lacking, the habitat model for juvenile fish cannot be verified. However, river reaches around the study area was regarded as important habitat for juvenile *C. guichenoti* based on ecology expert's experience in field monitoring.

4.2.2. WUA-Q relationship

To exclusively analyze the relationship between flow discharge and WUA, habitat suitability and WUA were calculated without including the water temperature parameter in the model. The WUA was calculated for spawning and juvenile *C. guichenoti* for 17 different flow discharges, i.e., from 500 m^3/s to 3500 m^3/s at 250 m^3/s intervals and from 3500 m^3/s to 5500 m^3/s at 500 m^3/s intervals, respectively (Fig. 10). The results revealed a unimodal relationship between the WUA and flow discharge for spawning fish and a decreasing relationship for juvenile fish. The suitable range of flow discharges for spawning fish ranged from 750 m^3/s to 3000 m^3/s. The preferred flow discharge values for juvenile fish were low (<1000 m^3/s), but the WUA remained high and did not change drastically when the flow discharges were larger than 1500 m^3/s.

4.2.3. Future scenario modeling

Using the habitat models, the time series of daily WUA for spawning and juvenile *C. guichenoti* were obtained and compared between or the baseline and climate change scenarios (Fig. 11). For spawning fish, the results showed a significant increase in WUA in April, May, September and October, and slight changes were observed from June to August in the climate change without hydropower operation scenarios. Comparisons of the WUA between the scenarios of climate change with and without hydropower operation showed that, under climate change with hydropower operation, the WUA greatly decreased in April and May (even close to baseline results) and greatly increased in September and October, which indicated that hydropower operation restrained the positive impacts of climate change on spawning habitat in April and May and enhanced this impact in September and October (Fig. 11, Spawning). Similar results were obtained for juvenile fish (Fig. 11, Juvenile). Because May is an important month for fish spawning, climate change and hydropower operation are expected to exert opposite effects on reproductive activities in spawning periods.

The total WUAs (TWUA) of spawning and juvenile fish were calculated for all scenarios and were compared (Fig. 12). For juvenile fish, the TWUA was calculated by adding the daily WUA values from a complete year. Since the spawning period lasts from April to July, the TWUA for spawning fish was calculated by adding the daily WUA across this period. The changes in the TWUA were also calculated and displayed in Table 3, in which the *B*, *BH*, *CC*, *CCH* represent the baseline, baseline with hydropower, climate change and climate change with hydropower scenarios, respectively. It was obvious that the TWUAs significantly increased for both spawning and juvenile fish in the scenarios of climate change without hydropower operation (Fig. 12, blue bar); this was especially true for spawning fish, for which the TWUAs increased by >34% ($(CC - B) / B$ in Table 3). This effect was maximized in the FF85-7 scenario and was weakest in the FF45-3 scenario. When considering hydropower operation along with the climate change scenarios (Fig. 12, red bar), a decrease in the TWUA was observed, which denoted that hydropower operation had a negative impact on fish habitat. This negative effect was obvious for spawning fish, for which the TWUAs decreased by >17% ($(CCH - CC) / CC$ and $(BH - B) / B$ in Table 3). However, compared to the baseline, the TWUAs were higher for both spawning and juvenile fish under the scenarios with the combined impacts of climate change and hydropower operation (Fig. 12, $(CCH - B) / B$ in Table 3). In general, spawning fish were more sensitive to climate change and hydropower operation.

5. Discussion

5.1. Impact of climate change and hydropower on flow discharge and water temperature

A recent IPCC report (IPPC, 2001) revealed that the average global temperature is expected to increase by 1.1–6.4 °C by the year 2100. The warming air temperature is expected to cause an increase in snowmelt in the upstream area of the JRB, resulting in an augmentation of

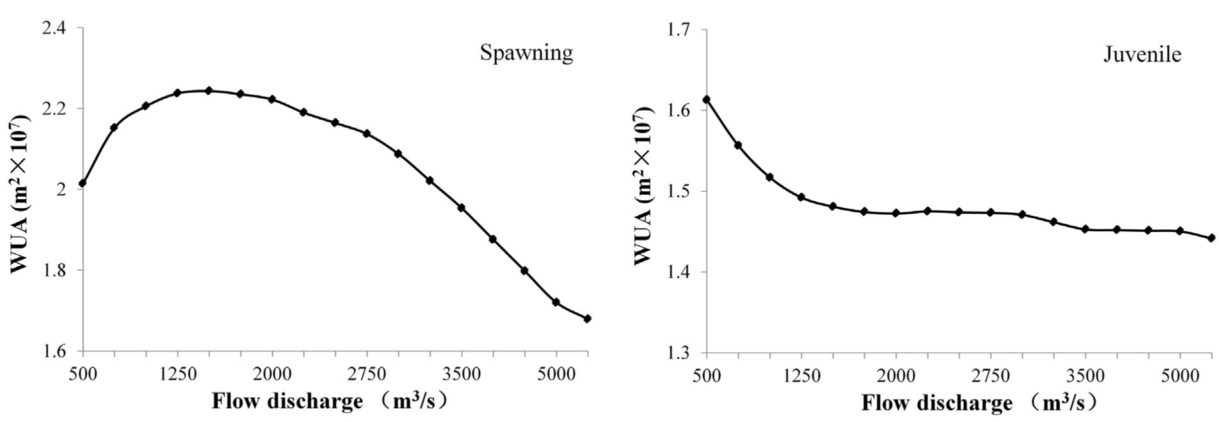

Fig. 10. WUA-flow discharge relationship for spawning and juvenile *C. guichenoti*.

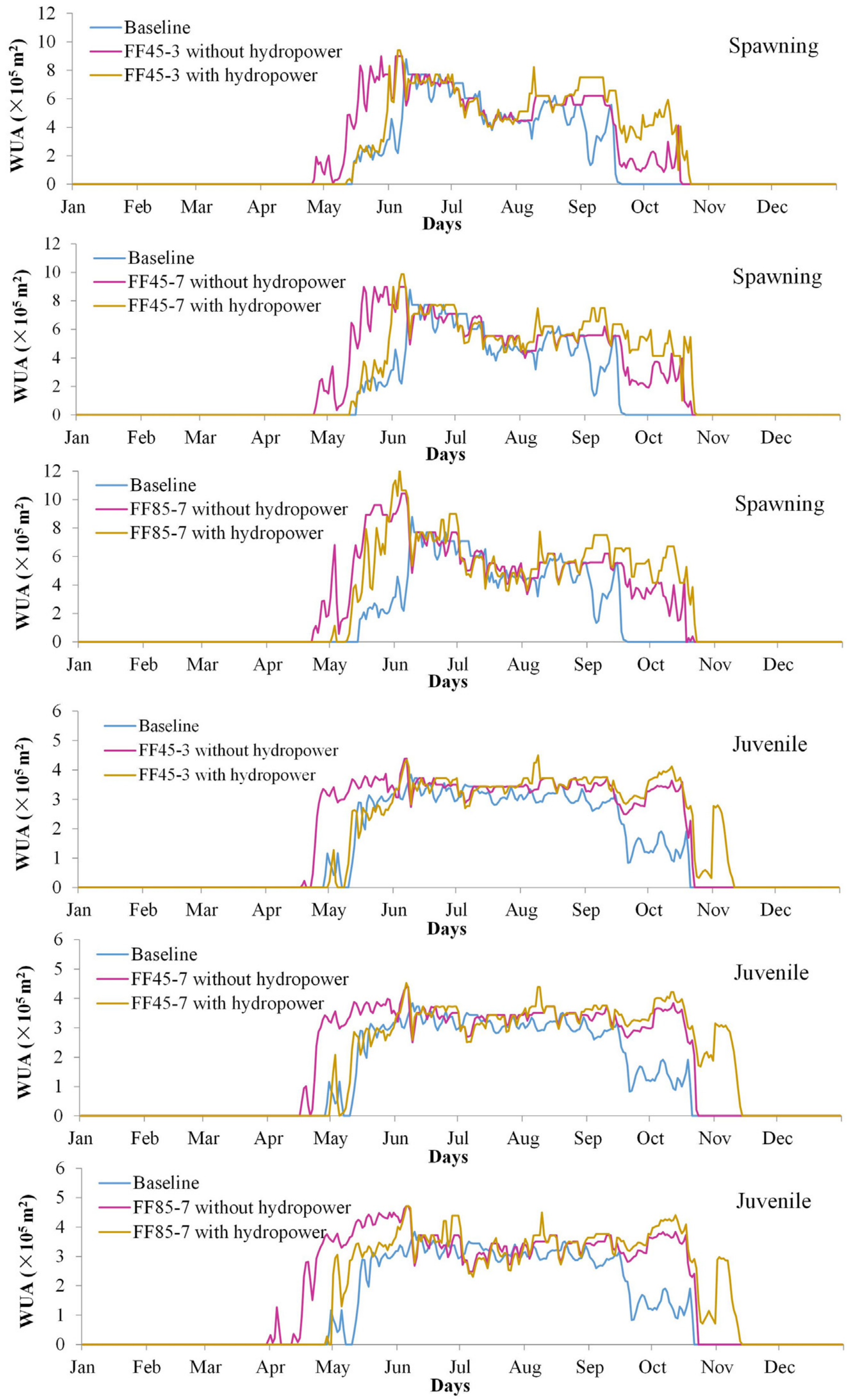

Fig. 11. Comparison of predicted daily WUA for spawning and juvenile *C. guichenoti* in different scenarios.

river runoff. This has been well captured by the hydrological model in the simulations of the FF45-3 and FF45-7 scenarios, especially during the summer months (Fig. 7, left). One would expect the similar behavior of flow discharges under the FF85-7 scenario (which uses the high-emission scenario RCP8.5). However, the modeled results showed a small decrease in the monthly mean flow discharge at Sanduizi (Fig. 7, left). Since the studied river reach is in a dry-hot valley region (Nanjun et al., 2002), rapid evapotranspiration is the dominant process in this area, and evaporation losses in the reservoir are significant (Zhang and Yang, 2014). Due to the flood control and power generation requirements in the JRB, hydropower alters the river flow regime at yearly, monthly and daily scales. For the studied river reach, the river flow is controlled by the upstream Guanyinyan hydropower station on the mainstream Jinsha River and by the Ertan hydropower station in the Yalong River (Fig. 1). However, the hydropower stations upstream and downstream of the studied river reach are cascaded, which makes it difficult to predict consistent changes in river flow. Climate change and hydropower would severely modify the annual flow regime in this reach by reducing the magnitude, frequency, and duration of flood peaks (Poff and Zimmerman, 2010). In the future, a more in-

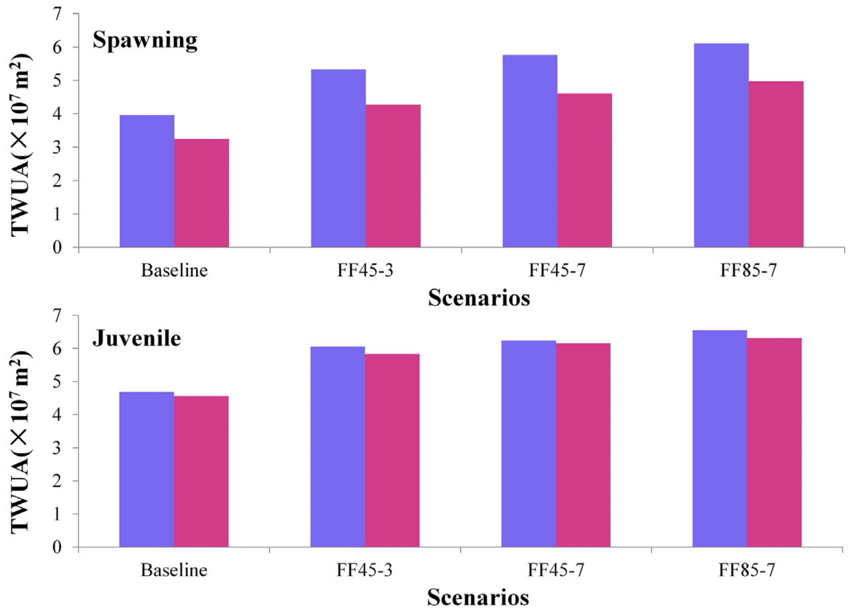

Fig. 12. The TWUA in baseline and climate change scenarios with and without hydropower for spawning and juvenile *C. guichenoti*. Blue bar: without hydropower; red bar: with hydropower. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

depth study could be performed using long-term hydrological data to fully analyze alterations to the hydrological regime caused by climate change and hydropower operation.

It was obvious from the prediction results that the warmer air temperature induced by climate change was assumed to result in an increase in water temperature, especially for the high-emission scenario RCP8.5 (FF85-7, Fig. 8, left). However, hypolimnetic discharges from hydropower stations change the water temperature regime downstream of the dam. Water is vertically stratified by temperature in the reservoirs, and the dams are designed to discharge the cold bottom water in the summer and the warm bottom water in the winter. Because of the recent construction of dams in the mainstream channel of the Jinsha River, the water temperature in the Jinsha River has become colder in the spring but hotter in the winter compared with previous observations. Given the cumulative effects on water temperature from the cascaded dams, the time required for the water temperature to increase to a certain normal degree can be delayed by one or more months (Wang et al., 2009). The predicted results under the combined effects of climate change and hydropower operation showed a clear decrease in water temperature in March and April, and this decrease was close to baseline conditions (Fig. 8, right). This indicated that the increase in water temperature due to climate change could weaken the hypolimnetic effects in the summer. However, the water temperature is expected to be further increased in the autumn and winter months (i.e., October to January) under the combined warming effects of climate change and hydropower operation (Fig. 8, right).

Table 3
Changes in the TWUA under scenarios of climate change with and without hydropower operation. $(CC - B)/B$ represents the percent change of the TWUA impacted only by climate change. $(BH - B)/B$ and $(CCH - CC)/CC$ represent the percent change of the TWUA impacted only by hydropower. $(CCH - B)/B$ represents the percent change of the TWUA impacted by both climate change and hydropower. *B*: baseline, *BH*: baseline with hydropower, *CC*: climate change without hydropower. *CCH*: climate change with hydropower.

Scenario	$(BH - B)/B$	$(CC - B)/B$	$(CCH - B)/B$	$(CCH - CC)/CC$
Spawning fish				
FF45-3	−18.1%	34.8%	7.5%	−20.2%
FF45-7		45.4%	18.8%	−18.3%
FF85-7		54.2%	28.0%	−17.0%
Juvenile fish				
FF45-3	−2.5%	29.3%	24.5%	−3.7%
FF45-7		33.2%	31.4%	−1.3%
FF85-7		39.7%	34.7%	−3.6%

5.2. Impact of climate change and hydropower on fish habitat

Water temperature is regarded as the most important habitat factor for *C. guichenoti* (Cheng et al., 2015). The prediction results showed that, for both spawning and juvenile fish, the TWUAs increased in the climate change scenarios (Fig. 12, blue bar). A comparison of the results of the three climate change scenarios showed that the TWUA continued to increase as the water temperature increased (Fig. 12, blue bar; Fig. 8, left). The temporal shifts in the daily WUAs were different in different months (Fig. 11). In April, May, September and October, the monthly mean discharges (Fig. 7, left) were mostly outside of the suitable range for fish habitat (Fig. 10); however, the daily WUAs significantly increased. During the flooding periods (i.e., from early June to August), the flow discharges in the climate change scenarios increased to become more unsuitable, but the daily WUAs did not significantly change. These results indicated that water temperature variation as a result of climate change was likely to be a key factor influencing the habitat quality of *C. guichenoti* in the future. Due to the expected increase in water temperature as a result of global warming, warm-water fish species with spawning periods in late spring and summer generally presented broader spawning periods and may colonize many newly suitable spawning sites (Kwon et al., 2015).

Compared to the scenarios of only climate change, the TWUA decreased under the scenarios with the combined effects of climate change and hydropower, especially for spawning fish (Table 3). Cold hypolimnetic discharges from reservoirs during the spawning months are the main reason for the observed reduction in the TWUA compared with the non-hydropower scenarios (Fig. 12, left). During the non-spawning months (i.e., September and October), the WUAs further increased due to the discharged warm water in the scenarios of climate

change with hydropower operation. It was difficult to predict whether there would be new habitats colonized in these months. For juvenile fish, although the WUAs decreased in the summer, some increases were observed in the autumn due to the impact of hydropower (Fig. 12, right). For this reason, the TWUA decreased less when considering hydropower operation along with the climate change scenarios (Table 3). However, suitable habitat areas still increased under the combined impacts of climate change and hydropower operation compared with the baseline conditions (Table 3). This means that climate change is likely to reduce the negative impacts caused by hydropower operation on the habitat of the target fish. Indeed, the positive impacts of climate change on the habitat quality of warm-water and eurythermic fish species have already been recorded (Null et al., 2012). Although the spawning habitat suitability of the eurythermic fish species in the JRB would be increased induced by climate change, the migration way would be blocked by the cascade dams and the fish could not reach the suitable spawning area. Therefore, the fish lifts and passages should be constructed for the cascade dams to enhance the passibility of the fish.

5.3. Potential impact on fish spawning

Due to the increase in water temperature caused by climate change, the WUAs clearly increased in April, which is a non-spawning month but directly precedes the spawning months. However, hydropower operation caused a decrease in the WUA that was very close to the baseline conditions observed in May (Fig. 11, Spawning, scenarios FF45-3 and FF45-7). Such temporal changes in available habitat may shift the spawning activities of *C. guichenoti*. Water temperature is the key factor influencing spawning of the fish and the lowest spawning water temperature is 18 °C (Tang et al., 2012). To avoid randomness and uncertainty, the start spawning day (SSD) was defined as the first day of five consecutive days in which the water temperature is >18 °C in this study. The SSDs and the ranges of water discharge and temperature in the five consecutive days for the different scenarios are displayed in Table 4, where it is shown that the water temperature and discharge in the five consecutive days are all within the suitable range for spawning fish. The SSD in the baseline scenario occurred in the middle of May (baseline in Table 4), but it shifted to the early June under the impact of hydropower (baseline+ in Table 4). Indeed, recent studies have shown that the spawning of *C. guichenoti* has been delayed by cascaded dam construction in the Jinsha River (Yang et al., 2017; Zhang et al., 2018). The results in Table 4 show that climate change would move the SSD forward several days, and this shift would be greater than two weeks in scenario FF85-7 compared to the baseline. The SSD could return to very close to the baseline in the scenarios of climate change with hydropower operation, with the exception of scenario FF85-7 with hydropower operation, in which the SSD shifts to an earlier time. This indicated that although hydropower operation postponed the spawning time, future climate change will likely restore the SSD to close to natural conditions. There are 15 species that are recorded to spawn in the Jinsha River, and most of them begin spawning at a water temperature of 18 °C or higher (Cheng et al., 2015). Considering the cumulative effects of the ten cascaded dams on water temperature, the timing of the rise in water temperature to 18 °C is expected to be delayed, ultimately postponing the start of fish spawning by >1 month (Yun et al., 2006; Wang et al., 2009). Hydropower operation is assumed to shorten the spawning and growing seasons for young-of-the-year juveniles before winter and would decrease their energy accumulation, thereby reducing their overwintering survival rates (Zhang et al., 2011). Therefore, climate change will likely eliminate the negative effects caused by hydropower operation on fish spawning, survival and population sizes in the future.

Table 4
The SSD and the range of water discharges (Q) and water temperatures (T) on the five consecutive days for different scenarios. The symbol "+" represents scenarios with hydropower operation.

Scenarios	SSD	Q	T
Baseline	5/19	2884–3162	18.1–18.7
Baseline+	6/4	2765–3179	18.0–19.2
FF45-3	5/11	2891–3215	18.2–19.3
FF45-7	5/10	2578–3010	18.6–19.5
FF85-7	5/1	1917–2047	18.7–19.6
FF45-3+	5/21	2546–2925	18.3–18.5
FF45-7+	5/17	2925–3205	18.2–18.8
FF85-7+	5/11	2619–3147	18.4–18.9

Unlike the positive effects on warm-water fish, the spawning periods of cold-water fishes (generally in the early spring and winter) would be shortened, and the available habitat areas are assumed to decrease (Comte et al., 2013). Many studies have documented negative effects on the habitat suitability of cold-water fish species, mainly for salmonids. Cold-water fish species are mainly distributed in the upper and middle mainstream regions of the Jinsha and Yalong rivers. Through a sampling campaign conducted in 2013–2014, 17 cold-water fish species were collected. The spawning water temperature range for nine of these species has been determined. The spawning temperature of these fish species are generally below 18 °C, and the spawning periods are typically from autumn to early spring. It can be predicted that these fish would be significantly affected by increases in water temperature caused by future global warming. Meanwhile, there are many planned cascade dams in the upper and middle mainstream of the Jinsha and Yalong Rivers. Hydropower operation can increase the water temperature by approximately 1–3 °C from October to January (Fig. 3). Therefore, the spawning suitability of these cold-water fish species will likely significantly decrease under the combined impacts of future climate change and dam construction and operation. The spawning periods are assumed to be shortened, and the spawning sites would disappear; furthermore, these species may even be confronted with a possible risk of extinction in the JRB. Fish reproduction is a key life-history stage, and further studies must be conducted to quantitatively analyze the effects of climate change on the reproductive activity and egg incubation, especially for cold-water fish species in the JRB.

5.4. Application of the modeling approach and results for river management

The hierarchical model approach proposed in this study helps to model river conditions and represents a useful tool that can be used to predict climate change and hydropower impacts on fish habitats. The method is not limited to small-scale river reaches; rather, it can also be used to model large river networks if sufficient data are available. Additional variables can be included in future applications of the model framework, including water level fluctuation, which may help to predict hydrological effects on fish habitat. This could help in identifying the main factors that influence fish and other aquatic organisms and in predicting general trends triggered by changes in climate and hydropower operation. The construction and operation of large hydropower stations in the JRB have already caused a series of ecosystem impacts, including recent declines in fish populations and ecosystem degradation. Some adaptive measures should be and have been employed to restore and conserve fish habitat and populations, such as the restoration of natural flow regimes, artificial reproduction and releasing, and construction of fish passages (Cheng et al., 2015). However, climate change and hydropower operation are expected to have disparate effects on different fish ecotypes (e.g., cold-water and warm-water fish species); thus, adaptive measures must be customized for each particular case. Moreover, the present work can help managers compare the cost and effectiveness of restoration measures and propose long-term measures under the background of climate change and hydropower construction in the JRB.

6. Conclusions

In this study, a multi-scale coupled eco-hydrological-hydraulic model framework was developed to predict and analyze the impacts of climate change and hydropower operation on the habitat suitability of spawning and juvenile *C. guichenoti* in a reach of the Jinsha River. The hierarchical model framework included global circulation models that were downscaled to the regional JRB, a hydrological model of the JRB used to predict flow discharge at the basin scale, a water temperature model and a 1D hydraulic model at the segment scale, and a 2D hydraulic model and a fuzzy logic-based fish habitat evaluation model at the studied river reach. Using scenario predictions, the changes in flow discharge and temperature and their influence on fish habitat suitability were evaluated along the model cascade. Model simulations revealed that (1) the magnitude and direction of the change in flow discharge varied for different scenarios of climate change with and without hydropower; (2) water temperature increased for all climate change scenarios, but it decreased in spring and summer and further increased in autumn and winter due to the impacts of hydropower operation; (3) temporal changes in the habitat suitability of spawning and juvenile fish shifted due to the impacts of climate change and hydropower operation. The weighted usable habitat areas (WUAs) increased under the impact of climate change, but this positive effect was reduced when the impacts of hydropower operation were considered. However, the WUA ultimately increased under the combined effects of future climate change and hydropower operation. (4) Water temperature rise impacted by climate change and changes in the water temperature regime due to hydropower operation were the main reasons for the observed opposite effects on fish habitat. (5) Climate change is expected to move the spawning time and reduce the negative impacts on the target fish and other warm-water fish species following hydropower operation in the JRB. (6) Climate change will likely aggravate the negative effects induced by hydropower operation on spawning for cold-water fish species, as both would probably increase the water temperature during spawning periods, which deserves more research in the future. The different impacts among species are assumed to induce variations in fish community structures and would eventually result in various ecological responses, including alterations in species distributions, biodiversity, productivity, and food web structures and functions. Therefore, some adaptive and long-term measures should be formulated to protect the river ecology against climate change and hydropower construction in the JRB.

Prediction tools such as that described in this work are key instruments to quantify how the habitat quality and distribution of fish species with different ecotypes will be altered by a changing environment. However, this is a challenging task due to the complex interactions of the many factors involved. Although this work focused on the effects of varying flow discharge and water temperature, other factors such as river morphology, water quality or biological factors (including food resources and predators) are also important. An improvement to the proposed methodology should rely on more complex models that include these factors. Moreover, if more observed ecological data were to become available, the effects on fish habitat would be better predicted and more reliable.

Acknowledgments

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Appendix A. Appendix

Table A-1
Fuzzy rules of water temperature (T), water depth (D), flow velocity (V) and habitat suitability index (HSI) for spawning *C. guichenoti*. VL—very low; L—low; M—medium; H—high; VH—very high; WHE—whatever.

T	D	V	HSI	T	D	V	HSI	T	D	V	HSI
VL	**WHE**	**WHE**	L	M	VL	VL	L	H	VL	VL	L
L	VL	VL	L	M	VL	L	L	H	VL	L	L
L	VL	L	L	M	VL	M	L	H	VL	M	L
L	VL	M	L	M	VL	H	L	H	VL	H	L
L	VL	H	L	M	VL	VH	L	H	VL	VH	L
L	VL	VH	L	M	L	VL	L	H	L	VL	L
L	L	VL	L	M	L	L	M	H	L	L	L
L	L	L	L	**M**	**L**	**M**	**H**	H	L	M	M
L	L	M	M	M	L	H	M	H	L	H	L
L	L	H	L	M	L	VH	L	H	L	VH	L
L	L	VH	L	M	M	VL	L	H	M	VL	L
L	M	VL	L	**M**	**M**	**L**	**H**	H	M	L	L
L	M	L	L	**M**	**M**	**M**	**VH**	H	M	M	M
L	M	M	M	**M**	**M**	**H**	**H**	H	M	H	L
L	M	H	L	M	M	VH	L	H	M	VH	L
L	M	VH	L	M	H	VL	L	H	H	VL	L
L	H	VL	L	M	H	L	M	H	H	L	L
L	H	L	L	**M**	**H**	**M**	**H**	H	H	M	M
L	H	M	M	M	H	H	M	H	H	H	L
L	H	H	L	M	H	VH	L	H	H	VH	L
L	H	VH	L	M	VH	VL	L	H	VH	VL	L
L	VH	VL	L	M	VH	L	L	H	VH	L	L
L	VH	L	L	M	VH	M	L	H	VH	M	L
L	VH	M	L	M	VH	H	L	H	VH	H	L
L	VH	H	L	M	VH	VH	L	H	VH	VH	L
L	VH	VH	L					VH	**WHE**	**WHE**	L

Table A-2
Fuzzy rules of water temperature (T), water depth (D), flow velocity (V) and habitat suitability index (HSI) for juvenile *C. guichenoti*. VL—very low; L—low; M—medium; H—high; VH—very high; WHE—whatever.

T	D	V	HSI	T	D	V	HSI	T	D	V	HSI
VL	**WHE**	**WHE**	L	M	VL	L	L	H	VL	L	L
L	VL	L	L	M	VL	M	L	H	VL	M	L
L	VL	M	L	M	VL	H	L	H	VL	H	L
L	VL	H	L	M	VL	VH	L	H	VL	VH	L
L	VL	VH	L	M	L	L	M	H	L	L	L
L	L	L	L	**M**	**L**	**M**	**H**	H	L	M	M
L	L	M	M	M	L	H	M	H	L	H	L
L	L	H	L	M	L	VH	L	H	L	VH	L
L	L	VH	L	**M**	**M**	**L**	**H**	H	M	L	L
L	M	L	L	**M**	**M**	**M**	**VH**	H	M	M	M
L	M	M	M	**M**	**M**	**H**	**H**	H	M	H	L
L	M	H	L	M	M	VH	L	H	M	VH	L
L	M	VH	L	M	H	L	M	H	H	L	L
L	H	L	L	**M**	**H**	**M**	**H**	H	H	M	L
L	H	M	M	M	H	H	M	H	H	H	L
L	H	H	L	M	H	VH	L	H	H	VH	L
L	H	VH	L	M	VH	L	L	H	VH	L	L
L	VH	L	L	M	VH	M	L	H	VH	M	L
L	VH	M	L	M	VH	H	L	H	VH	H	L
L	VH	H	L	M	VH	VH	L	H	VH	VH	L
L	VH	VH	L					VH	**WHE**	**WHE**	L

References

Abell, R., 2002. Conservation biology for the biodiversity crisis: a freshwater follow-up. Conserv. Biol. 16, 1435–1437.

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu. Rev. Ecol. Evol. Syst. 35, 257–284.

Bobbi, C.J., Warfe, D.M., Hardie, S.A., 2014. Implementing environmental flows in semi regulated and unregulated rivers using a flexible framework: case studies from Tasmania. River Res. Appl. 30, 578–592.

Bovee, K.D., 1998. A guide to stream habitat analysis using the instream flow incremental methodology. Report 2, 19–28.

Brown, L.R., Komoroske, L.M., Wagner, R.W., Morgan-King, T., May, J.T., Connon, R.E., et al., 2016. Coupled downscaled climate models and ecophysiological metrics forecast habitat compression for an endangered estuarine fish. PLoS One 11, e0146724.

Cheng, F., Li, W., Castello, L., Murphy, B.R., Xie, S., 2015. Potential effects of dam cascade on fish: lessons from the Yangtze River. Rev. Fish Biol. Fish. 25, 569–585.

Comte, L., Buisson, L., Daufresne, M., Grenouillet, G., 2013. Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. Freshw. Biol. 58, 625–639.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z., Knowler, D.J., Lévêque, C., et al., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163–182.

Ficke, A.D., Myrick, C.A., Hansen, L.J., 2007. Potential impacts of global climate change on freshwater fisheries. Rev. Fish Biol. Fish. 17, 581–613.

Ficklin, D.L., Stewart, I.T., Maurer, E.P., 2013. Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. Water Resour. Res. 49, 2765–2782.

Guse, B., Kail, J., Radinger, J., Schroder, M., Kiesel, J., Hering, D., et al., 2015. Eco-hydrologic model cascades: simulating land use and climate change impacts on hydrology, hydraulics and habitats for fish and macroinvertebrates. Sci. Total Environ. 533, 542–556.

Hauer, C., Unfer, G., Holzmann, H., Schmutz, S., Habersack, H., 2013. The impact of discharge change on physical instream habitats and its response to river morphology. Clim. Chang. 116, 827–850.

Heino, J., Virkkala, R., Toivonen, H., 2009. Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. Biol. Rev. 84, 39–54.

Hernandez, J.G., Jordan, F., Dubois, J., Boillat, J.L., Schleiss, A., 2007. Routing System II — Modélisation d'écoulements dans des systèmes hydrauliques. Neuroquantology 28, 395–416.

Im, D., Kang, H., Kim, K.-H., Choi, S.-U., 2011. Changes of river morphology and physical fish habitat following weir removal. Ecol. Eng. 37, 883–892.

IPPC, 2001. The Scientific Basis. Contribution of Workong Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jenkins, M., 2003. Prospects for biodiversity. Science 302, 1175–1177.

Jochem Kail, B.G., Radinger, Johannes, Schröder, Maria, Kiesel, Jens, Kleinhans, Maarten, Schuurman, Filip, Fohrer, Nicola, Hering, Daniel, Wolter, Christian, 2015. A modelling framework to assess the effect of pressures on river abiotic habitat conditions and biota. PLoS One 10, e0130228.

Junker, J., Heimann, F.U.M., Hauer, C., Turowski, J.M., Rickenmann, D., Zappa, M., et al., 2015. Assessing the impact of climate change on brown trout (*Salmo trutta fario*) recruitment. Hydrobiologia 751, 1–21.

Kwon, Y.-S., Bae, M.-J., Hwang, S.-J., Kim, S.-H., Park, Y.-S., 2015. Predicting potential impacts of climate change on freshwater fish in Korea. Ecol. Inform. 29, 156–165.

Liu, J., 2004. A quantitative analysis on threat and priority of conservation order of the endemic fishes in upper reaches of the Yangtze River. China Environ. Sci. 4, 12–16 (in Chinese).

Liu, L., Wu, G., Wang, Z., 1990. Reproduction ecology of *Coreius heterodon* (Bleeker) and *Coreius guichenoti* (Sauvage et Dabry) in the mainstream of the Changjiang River after the construction of Gezhouba Dam. Acta Hydrobiol. Sin. 14, 205–215 (in Chinese).

Malmqvist, B., Rundle, S., 2002. Threats to the running water ecosystems of the world. Environ. Conserv. 29, 134–153.

Mantua, N., Tohver, I., Hamlet, A., 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Clim. Chang. 102, 187–223.

Mocq, J., St-Hilaire, A., Cunjak, R.A., 2013. Assessment of Atlantic salmon (*Salmo salar*) habitat quality and its uncertainty using a multiple-expert fuzzy model applied to the Romaine River (Canada). Ecol. Model. 265, 14–25.

Mohseni, O., Stefan, H.G., Eaton, J.G., 2003. Global warming and potential changes in fish habitat in U.S. streams. Clim. Chang. 59, 389–409.

Munoz-Mas, R., Lopez-Nicolas, A., Martinez-Capel, F., Pulido-Velazquez, M., 2016. Shifts in the suitable habitat available for brown trout (*Salmo trutta* L.) under short-term climate change scenarios. Sci. Total Environ. 544, 686–700.

Nanjun, L., Liqun, G., Guangtao, M., Xiangjing, F., Shaolong, W., Ke, H., et al., 2002. Analysis and research on diversity law of plateau mountainous region system of the Jinshajiang River valley. J. Beijing Forest. Univ. 24, 31–38 (in Chinese).

Noack, M., Schneider, M., Wieprecht, S., 2013. The habitat modelling system CASiMiR: a multivariate fuzzy approach and its applications. Ecohydraulics: An Integrated Approach. John Wiley & Sons.

Null, S.E., Viers, J.H., Deas, M.L., Tanaka, S.K., Mount, J.F., 2012. Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. Clim. Chang. 116, 149–170.

Palmer, M.A., Lettenmaier, D.P., Poff, N.L., Postel, S.L., Richter, B., Warner, R., 2009. Climate change and river ecosystems: protection and adaptation options. Environ. Manag. 44, 1053–1068.

Papadaki, C., Soulis, K., Munoz-Mas, R., Martinez-Capel, F., Zogaris, S., Ntoanidis, L., et al., 2016. Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. Sci. Total Environ. 540, 418–428.

Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194–205.

Poff, L.R., Olden, J.D., Strayer, D.L., 2012. Climate Change and Freshwater Fauna Extinction Risk. Island Press/Center for Resource Economics.

Pragana, I., Boavida, I., Cortes, R., Pinheiro, A., 2017. Hydropower plant operation scenarios to improve brown trout habitat. River Res. Appl. 33, 364–376.

Preston, B.L., 2006. Risk-based reanalysis of the effects of climate change on U.S. cold-water habitat. Clim. Chang. 76, 91–119.

Rahel, F.J., Keleher, C.J., Anderson, J.L., 1996. Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: response to climate warming. Limnol. Oceanogr. 41, 1116–1123.

Schaefli, B., Hingray, B., Niggli, M., Musy, A., 2005. A conceptual glacio-hydrological model for high mountainous catchments. Hydrol. Earth Syst. Sci. 9, 95–109.

Schindler, D.W., 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Can. J. Fish. Aquat. Sci. 58, 18–29.

Schneider, M., Kopecki, I., Eberstaller, J., Frangez, C., Tuhtan, J.A., 2012. Application of CASiMiR-GIS for the simulation of brown trout habitat during rapid flow changes. International Symposium on Ecohydraulics.

Segurado, P., Branco, P., Jauch, E., Neves, R., Ferreira, M.T., 2016. Sensitivity of river fishes to climate change: the role of hydrological stressors on habitat range shifts. Sci. Total Environ. 562, 435–445.

Sharma, S., Jackson, D.A., Minns, C.K., Shuter, B.J., 2007. Will northern fish populations be in hot water because of climate change? Glob. Chang. Biol. 13, 2052–2064.

Sievert, N.A., Paukert, C.P., Tsang, Y.-P., Infante, D., 2016. Development and assessment of indices to determine stream fish vulnerability to climate change and habitat alteration. Ecol. Indic. 67, 403–416.

Steffler, P., Blackburn, J., 2002. Two-dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat Introduction to Depth Averaged Modeling and User's Manual. River2D User's Manual.

Swiss Agency for Development and Cooperation, 2016. Jinsha River Basin Integrated Water Resources and Risk Management Under Changing Climate. https://www.weadapt.org/placemarks/maps/view/25966.

Tang, H.Y., Yang, Z., Gao, S.B., Chen, J.S., Zhang, Y.C., Wan, L., et al., 2012. Status of fish resources of early life history stages of *Coreius guichenoti* in the middle reaches of the Jinsha River. Sichuan J. Zool. 31, 416–421.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., et al., 2003. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. U. S. A. 100, 8074.

Wang, B., Huang, W., Yin, Z., 2009. On ecological flow impact of large cascade reservoirs. Resour. Environ. Yangtze Basin 18, 860–864 (in Chinese).

Wenger, S.J., Isaak, D.J., Luce, C.H., Neville, H.M., Fausch, K.D., Dunham, J.B., Dauwalter, D.C., Young, M.K., Elsner, M.M., Rieman, B.E., Hamlet, A.F., Williams, J.E., 2011a. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proc. Natl. Acad. Sci. U. S. A. 108, 14175.

Wenger, S.J., Isaak, D.J., Luce, C.H., Neville, H.M., Fausch, K.D., Dunham, J.B., et al., 2011b. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proc. Natl. Acad. Sci. U. S. A. 108, 14175–14180.

Woodward, G., Perkins, D.M., Brown, L.E., 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 365, 2093–2106.

Wu, J., Huang, J., Han, X., Xie, Z., Gao, X., 2003. Ecology. Three-Gorges Dam—experiment in habitat fragmentation? Science 300, 1239.

Xu, W., Qiao, Y., Chen, X.J., Cai, Y.P., Yang, Z., Liu, H.G., 2015. Spawning activity of the four major Chinese carps in the middle mainstream of the Yangtze River, during the Three Gorges Reservoir operation period, China. J. Appl. Ichthyol. 31, 846–854.

Yang, Z., Tang, H., Tao, J., Zhao, N., 2017. The effect of cascaded huge dams on the downstream movement of *Coreius guichenoti* (Sauvage & Dabry de Thiersant, 1874) in the upper Yangtze River. Environ. Biol. Fish. 1–10.

Yi, Y., Tang, C., Yang, Z., Chen, X., 2014. Influence of Manwan Reservoir on fish habitat in the middle reach of the Lancang River. Ecol. Eng. 69, 106–117.

Yun, D., Jia, L.I., Ran, L.I., Ke-Feng, L.I., 2006. Impact of reservoir operation on the water temperature downstream of Xiluodu Power Station. J. Sichuan Univ. 38, 65–69.

Zhang, X., Yang, S., 2014. Climate change and anthropogenic impact on water discharge in the Yangtze River over last 56 years (1956–2011). Resour. Environ. Yangtze Basin 23, 1729–1739 (in Chinese).

Zhang, G., Wu, L., Li, H., Liu, M., Cheng, F., Murphy, B.R., et al., 2011. Preliminary evidence of delayed spawning and suppressed larval growth and condition of the major carps in the Yangtze River below the Three Gorges Dam. Environ. Biol. Fish 93, 439–447.

Zhang, P., Yang, Z., Cai, L., Qiao, Y., Chen, X., Chang, J., 2018. Effects of upstream and downstream dam operation on the spawning habitat suitability of *Coreius guichenoti* in the middle reach of the Jinsha River. Ecol. Eng. 120, 198–208.